LOWEN & *TEPPER

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(6) DYNAMICS OF PIN PALLET RUNAWAY ESCAPEMENT,

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ABSTRACT

1. INTRODUCTION

This paper reports on the development of a simulation of a constant input torque pin pallet runaway escapement by the present authors [1][1]. The resulting program provides a basic tool for the analysis and synthesis of various safing and arming devices.

The dynamics of the regimes of motion of the escapement were ~~have~~ been formulated. Coupled motion, with continuous contact between escape wheel tooth face and pallet pin, impact of the pin on the tooth face and uncoupled, or free, motion of these mechanism components were considered. The associated regime equations apply to entrance as well as exit conditions. Sensing expressions for the determination of the instantaneous positions of the pallet pin and the escape wheel form the basis of the controls of the computer program. ~~In addition,~~ the sensing equations indicate the presence of such pathological conditions as tip or back face contact. The simulation ~~has been~~ was applied to the timing mechanism of the M525 fuze. The influence of changes in such parameters as escape wheel input torque, pallet moment of inertia, center distance, pallet radius, etc., on the mechanism delay time ~~have been~~ were explored in detail by appropriate computer runs. The results, ~~which are shown here,~~ compare favorably with existing experimental data.

ABSTRACT

This effort represented an extension of the work of M. E. Anderson and S. L. Redmond [2]. New methods of contact kinematics for the coupled motion, of contact sensing, and of computational

[1] Numbers in brackets refer to refences in section 7.

controls were developed.

2. DESCRIPTION OF MOTION REGIMES AND SENSING TOOLS

The following describes the various dynamic regimes of the simulation, together with the applicable sensing parameters.

A. COUPLED MOTION

Figure 1 shows the entrance pallet pin as it is driven in coupled motion by tooth No. 1 of the escape wheel. The escape wheel angle ϕ is defined by the line from the escape wheel pivot O_s to the tip of the contacting tooth (or the one about to make contact) and the center line connecting O_s to the pallet pivot O_p. Similarly, the angle ψ, which is defined by the line from O_p to the active pallet pin center (entrance or exit) and the center line, describes the motion of the pallet. The escape wheel is driven by the constant moment T in the positive direction of rotation. While it is assumed that friction acts on the pallet pin-escape wheel tooth interface, it is neglected at both pivot pairs since investigation showed that its effects are negligible when the pivots are of the usual small diameter. The mathematical description of coupled motion is furnished by a non-linear second order differential equation in the escape wheel angle ϕ. The presence of the pallet is reflected back to the escape wheel in terms of a position dependent moment of inertia.

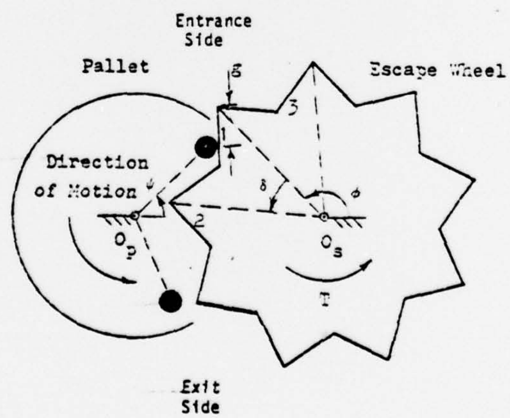

Figure 1 Coupled Motion

The quantity g, which represents the distance from the contact point to the tip of the escape wheel tooth, is used to determine the progress of coupled motion. Once the angle ϕ has been determined from the solution of the differential equation, both ψ and g may be computed from appropriate kinematic relationships.

B. FREE MOTION

When coupled motion is completed, i.e. g=0, or when separation of contact occurs after impact, escape wheel and pallet

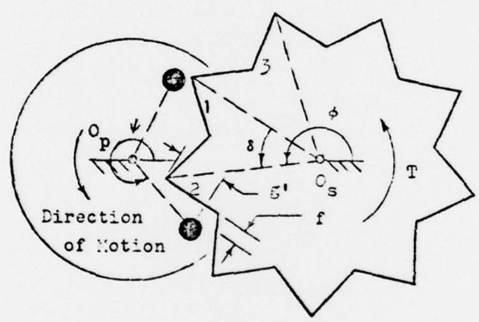

Figure 2 Free Motion

move independently of each other in free motion. Figure 2 shows this free motion for the exit phase of the action, i.e. the exit pallet pin is about to make contact with tooth No. 2 of the escape wheel. The constant torque T continues to act on the escape wheel, while the motion of the pallet depends only on its initial conditions. Again, any frictional retarding moments of the pivots are neglected. The motions of both components are represented by simple linear 2nd order differential equations. During this regime, position sensing is accomplished with the help of the quantities g' and f. The first of these quantities represents the distance of the pallet pin center from the tip of the escape wheel tooth, while the second measures the distance between the pallet pin and the tooth face. The solutions to the individual differential equations provide the angles ϕ and ψ. These are used to determine the above sensing parameters.

C. IMPACT

Impact follows free motion when both f=0 and g'<0, and when the relative velocity between the contact surfaces warrants it. (g' is negative because of the choice of the coordinate system.) Such an impact usually reverses the motion of the pallet (see Figure 3) and under certain circumstances also temporarily reverses the motion of the escape wheel.

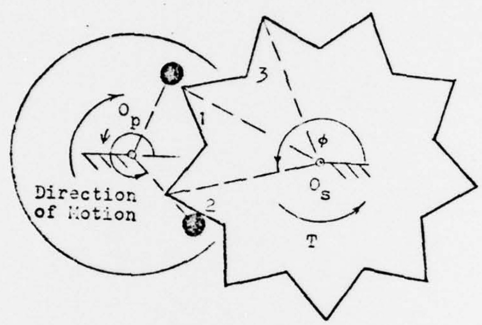

Figure 3 Exit Impact

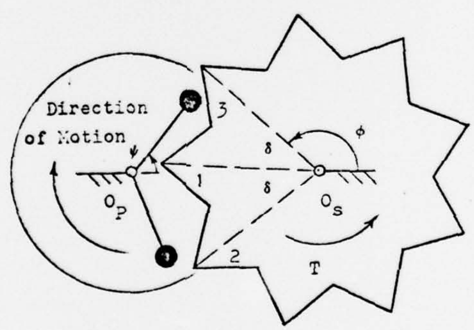

Figure 4 Impending Entrance Impact

Figure 4 shows free motion for the subsequent entrance phase of the mechanism, i.e. the top pallet pin is about to make contact with tooth No. 3 of the escape wheel. The simulation recognizes only contact on the front faces of the escape wheel teeth. This means that such pathological conditions as impact on the tips or on the back faces of the teeth are not considered. (The control quantities g and g' make it clear when such a condition exists and the computation can then be discontinued.)

3. ESCAPEMENT NOMENCLATURE

Figure 5 shows a schematic representation of the pin pallet escapement and indicates its basic geometric nomenclature.

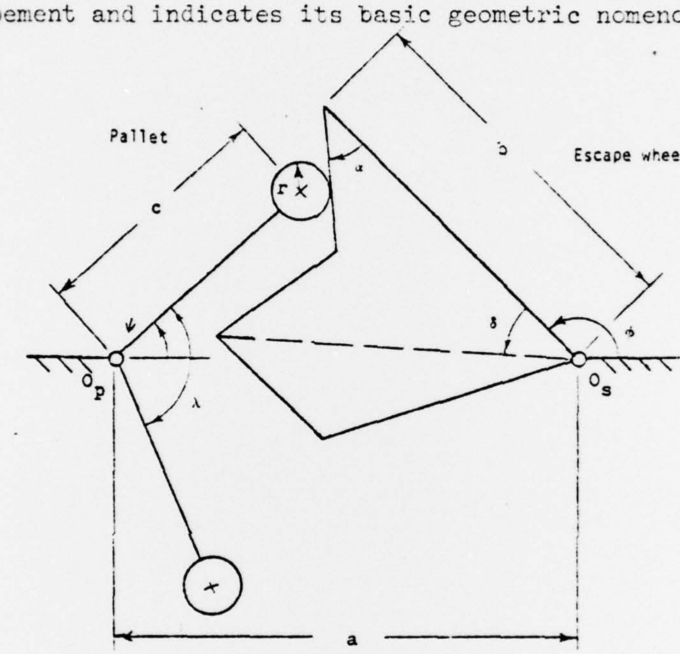

Figure 5 Escapement Nomenclature

a = Distance between pivots O_p and O_s
b = Escape wheel radius
c = Pallet radius (equal on entrance and on exit side)
r = Pallet pin radius (equal on entrance and on exit side)
α = Escape wheel tooth half angle
δ = Angle between escape wheel teeth
λ = Angle between pallet radii

4. DESCRIPTION OF COMPUTER PROGRAM

The following gives the essential steps of the computer program[2]. Figure 6 represents the associated flow chart. The main program starts the simulation with coupled motion on the entrance side for a starting angle $\phi = 135^\circ$. The total escape wheel angle is set

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[2]The program shown is written in FORTRAN for the CDC System at ARRADCOM, Dover, NJ.

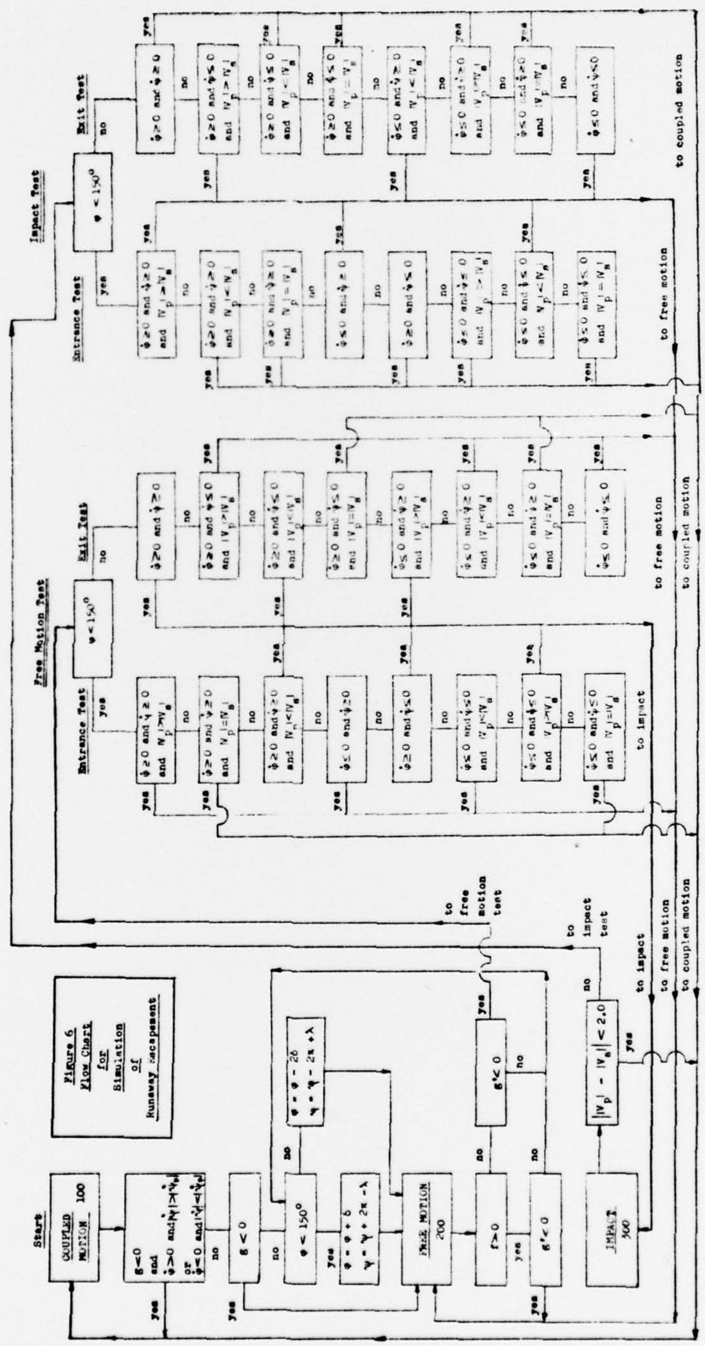

Figure 6
Flow Chart
for
Simulation
of
Runaway Escapement

to 0°. This choice of starting angle represents the approximate midpoint of the coupled motion of the example mechanism. The computation is terminated either when $t = .1$ seconds, or when the total escape wheel angle equals 310°. (See Section 5B).

A. COUPLED MOTION (location 100)

To solve the differential equation of coupled motion, the main program calls on a fourth order Runge-Kutta routine[3]. The angles ϕ and ψ, the total escape wheel angle, the angular velocities $\dot{\phi}$ and $\dot{\psi}$, as well as the control parameter g are computed for each time increment. The program continues coupled motion under the following circumstances:

(1) As long as $g<0$. (Because of the nature of the coordinate system, g is always negative while the pallet pin can make contact with the escape wheel tooth.)

(2) As long as, for a positive (CCW) rotation of the escape wheel, a succeeding absolute value of $\dot{\psi}$ is larger than the one obtained from the preceding computation. This condition is necessary, since in coupled motion when $\dot{\phi}$ is positive, the escape wheel can only drive the pallet but not slow it down. If such a slowdown is indicated, it means that pallet and escape wheel have separated and that free motion is taking place. A similar control is provided for a negative rotation of the escape wheel, which may occur after impact. When coupled motion is terminated, control is shifted to the subroutine containing the free motion equations (location 200). This is done directly if $g<0$. In case that $g\geq 0$, the main program must ascertain whether the preceding computations have been made for entrance or exit conditions, and accordingly, on which side the next contact will occur. In the sample mechanism, $g=0$ when ϕ is approximately 146° at entrance and approximately 207° at exit. Thus, if $g \geq 0$ and $\phi \leq 150°$, all possibility for entrance contact is ended and ϕ must be incremented by the tooth angle δ (see Figures 2 and 5) while ψ must be incremented by the angle $2\pi-\lambda$. For $g\geq 0$ and $\phi > 150°$, entrance action follows exit action and ϕ must be decremented by the angle 2δ (see Figure 4, where the new top tooth No. 3 comes into action). At the same time, the pallet angle is decremented by $-2\pi+\lambda$.

B. FREE MOTION (location 200)

After transferring the appropriate initial values from the main program, the subroutine containing the free motion

[3] RKGS Routine, IBM, System/360 Scientific Subroutine Package, (360A-CM-OX3) Version III.

equations computes the subsequent positions and angular velocities of pallet and escape wheel. In addition to the above quantities, the total escape wheel angle is continually computed. The decision whether or not to remain in this subroutine is made with the help of the sensing parameters f and g'.

If $f>0$ and $g'\leq 0$, free motion is continued without indexing. If $f>0$ and $g'>0$, free motion is also continued. Since now contact is no longer possible, indexing takes place.

If $f\leq 0$, control is returned unconditionally to the main program. If it finds in addition that $g'\geq 0$, indexing takes place and control is given back to the free motion subroutine. In case that both $f\leq 0$ and $g'<0$ contact is about to take place (or actually has just occurred). The program must now decide whether this contact just represents a close approach which will be followed by further free motion, or whether it is the beginning of coupled motion. To this end, the quantities V_p and V_s, which stand for the velocities normal to the pallet and escape wheel contact points, respectively, are computed in the entrance and exit free motion tests[4]. The first three cases of of the entrance free motion test of the main program are illustrated by Figure 7. With both angular velocities $\dot{\phi}$ and $\dot{\psi}$ positive, the following three possibilities exist:

(1) If $|V_p|>|V_s|$, the contacting surfaces will separate again and free motion will occur. Control remains with the free motion subroutine (location 200).

(2) If $|V_p| =|V_s|$, the escape wheel will start driving the pallet in coupled motion, and control must be transferred to the coupled motion subroutine (location 100).

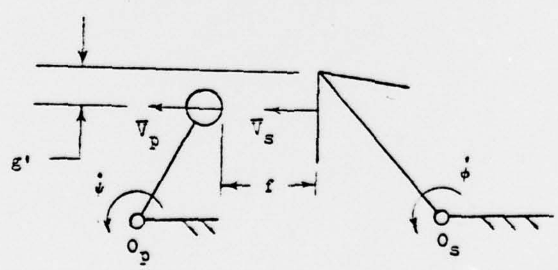

Figure 7 Entrance Free Motion Test
($\dot{\phi}$ and $\dot{\psi}$ are positive and distance f is exaggerated)

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[4] Under the present circumstances, if $\phi<150°$, only top contact can follow, while $\phi>150°$ means that bottom contact will occur.

(3) If $|V_p| < |V_s|$, impact will occur, and control must be given to the impact subroutine (location 300).

The remainder of the free motion tests are constructed along similar lines for different combinations of angular velocity directions.

C. IMPACT (location 300)

The subroutine containing the impact equations uses the current values of the angular velocities $\dot{\phi}_i$ and $\dot{\psi}_i$, and computes the post-impact angular velocities $\dot{\phi}_f$ and $\dot{\psi}_f$ according to classical rigid body impact theory. (The tangential impact due to friction has been neglected).

After impact, control is returned to the main program, and it must be decided whether free or coupled motion follows. This is accomplished by comparing the post-impact velocities V_p and V_s in the impact tests. These are similar to the free motion tests.

If the contact velocities are vectorially equal to each other, or if the absolute value of the difference of their absolute magnitudes is less than 2.0 in/sec (considered a small quantity), control is transferred to coupled motion. If this velocity difference is greater than the above criteria, computation is transferred to free motion.

5. EXAMPLE MECHANISM

The pin pallet escapement of the M525 fuze was used as an example mechanism. The following first gives the dimensions of the basic escapement (standard configuration) and then discusses certain other data and computed values which are of importance for the computer simulation.

A. DIMENSIONS OF STANDARD CONFIGURATION (See Fig. 5)

The standard configuration has the following dimensions:

$a = .193$ in. (mean center distance) $b = .1583$ in.
$c = .0968$ in $r = .0136$ in.
$\alpha = 40°$ $\lambda = 109.337°$
$I_p = .91 \times 10^{-7}$ lb-sec^2-in. (moment of inertia of pallet)
$I_s = .17 \times 10^{-7}$ lb-sec^2-in. (moment of inertia of escape wheel)

B. GEAR TRAIN

The escape wheel of the M525 fuze is driven by a clock spring through a step-up gear train of ratio 45.98. The timing function of the fuze, which involves a delay of between two and four seconds, is accomplished once the spring has rotated the input gear through 310° and with that, the escape wheel through 45.98 times as many degrees. Since the beat of the escapement is generally well stabilized after one tooth cycle, the total fuze time may be obtained by multiplying the time corresponding to 310° of escape wheel rotation by the above gear ratio.

C. STANDARD TORQUE USED IN THE SIMULATION

Measurements on actual fuzes showed that the initial torque on the escape wheels varied between .0177 and .031 in-lb. Since the angle of rotation of the input gear is small, the decrease in torque is also relatively small. Therefore, a constant torque was assumed in the simulation, and its standard value was chosen to be .0177 in-lb.

D. OTHER DIMENSIONS ASSOCIATED WITH STANDARD CONFIGURATION

For purposes of control in the computer program the following dimensions are of interest.

The maximum magnitude for the dimension g, associated with coupled motion is

$$g_{MAX} = -.055 \text{ in.}$$

This occurs for the entrance condition when

$$\phi_{gmn} = 132.4°$$

Because of this value, the program is started in coupled motion for $\phi = 135°$. For exit action, this angle becomes:

$$\phi_{gmx} = 187°$$

The escape wheel angle corresponding to g=0 is also of interest. For entrance action its magnitude is given by

$$\phi_{gon} = 146.3°$$

This angle is responsible for the somewhat larger indexing criterion of 150°. (See Section 4.) For exit action, this angle becomes:

$$\phi_{gox} = 206.512°$$

6. INFLUENCE OF VARIOUS PARAMETER CHANGES ON THE TOTAL FUZE TIME

The following reports on the results of numerous computer runs in which a single input or geometric parameter was varied in order to determine its influence on the total fuze time. In all cases, μ = .3 and ε = .25.

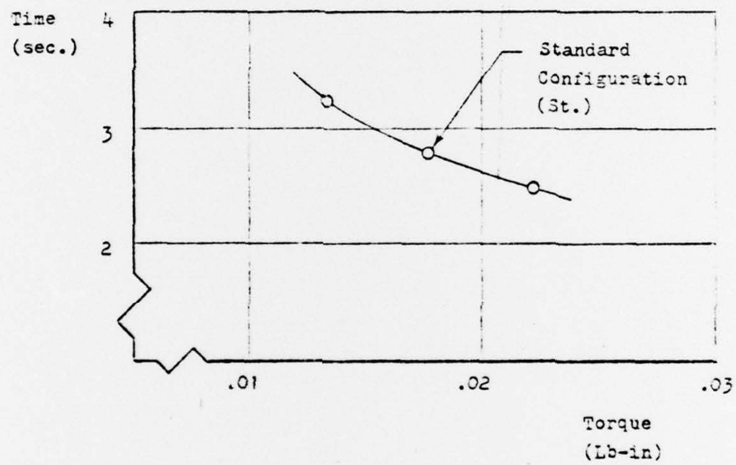

Figure 8 Influence of Escape Wheel Torque on Fuze Delay Time

Figure 8 shows the influence of the escape wheel torque. One may compare these timing results with those obtained from the well known empirical expression:

$$t_2 = t_1\sqrt{\frac{T_1}{T_2}}$$

If t_1 and T_1 represent fuze time and torque associated with the standard configuration, one obtains from the above:

For $T_2 = 75T_1$: $t_2 = 2.79\sqrt{\frac{1}{.75}}$ = 3.22 seconds

and for $T_2 = 1.25T_1$: $t_2 = 2.79\sqrt{\frac{1}{1.25}}$ = 2.49 seconds

The results of the simulation show excellent agreement with this empirical relationship, which has been confirmed time and again by experiment.

B. INFLUENCE OF PALLET MOMENT OF INERTIA

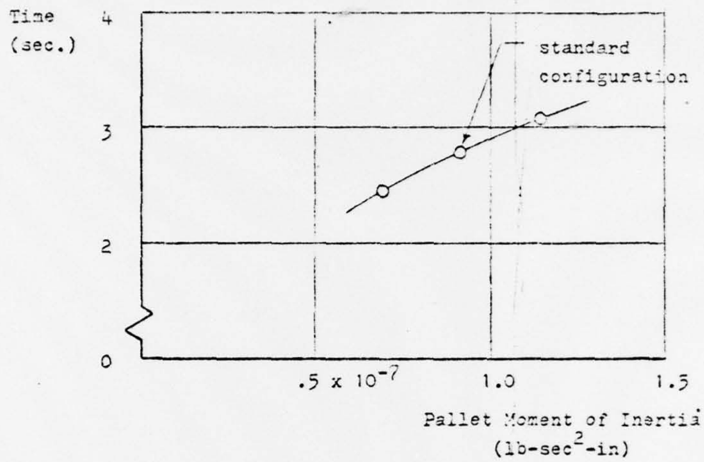

Figure 9 Influence of Pallet Moment of Inertia on Fuze Delay Time

Figure 9 shows that the total time of the fuze increases with an increase of the pallet moment of inertia. The ratio of any two periods is approximately proportional to the ratio of the square roots of the associated pallet inertias.

These results are also confirmed by many reports on experimentation.

C. INFLUENCE OF PALLET-ESCAPE WHEEL CENTER DISTANCE

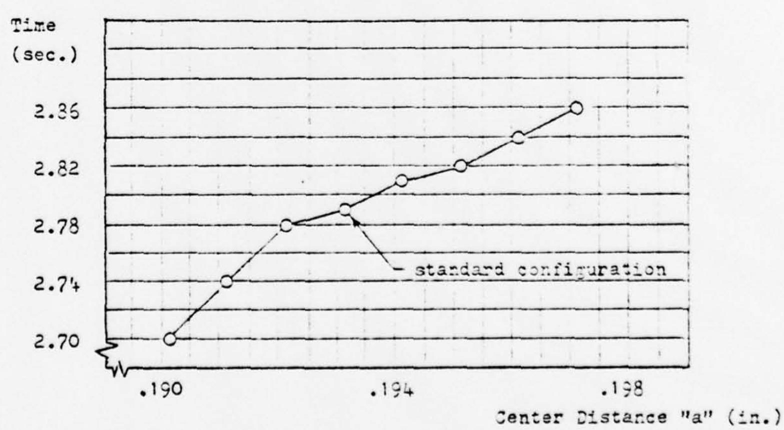

Figure 10 Influence of Pallet-Escape Wheel Center Distance on Fuze Delay Time

Figure 10 indicates that the fuze time increases as the center distance "a" is increased. For a total increase of .007 inches the time increase is approximately 7%. This result is generally confirmed by the experimentation of [2].

D. INFLUENCE OF PALLET RADIUS

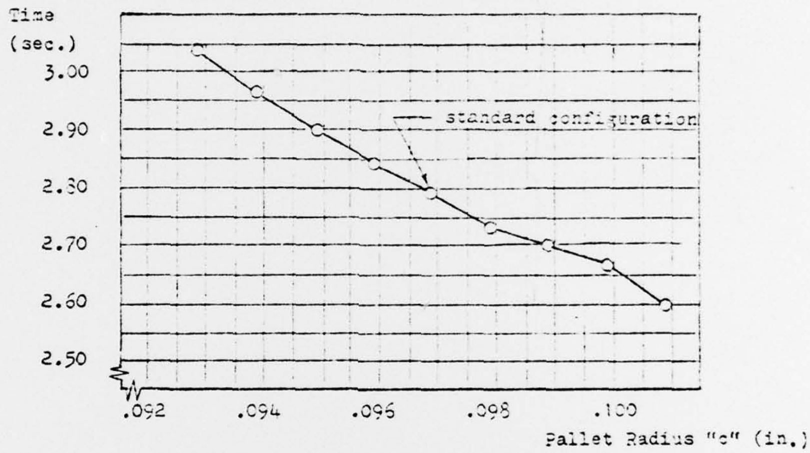

Figure 11 Influence of Pallet Radius on Fuze Delay Time

Figure 11 shows a continuous and quite dramatic decrease in fuze time as the pallet radius "c" is varied through .008 inches. Experimentation in [2] gives a good correlation with this result of the simulation.

E. INFLUENCE OF COEFFICIENT OF FRICTION

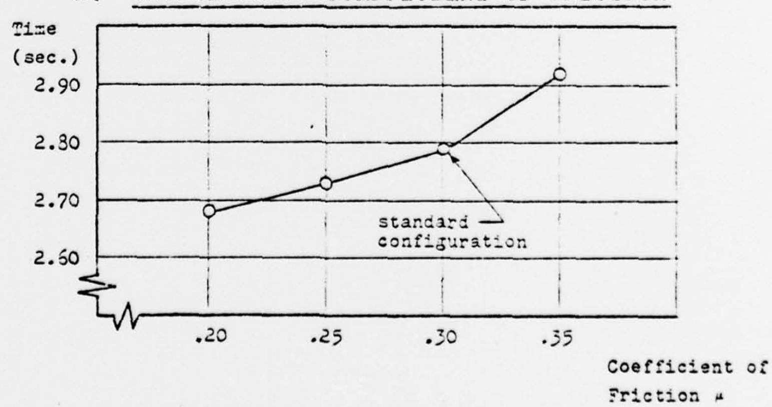

Figure 12 Influence of Coefficient of Friction of Coupled Motion on Fuze Delay Time

Figure 12 indicates that the fuze time increases as the coefficient of friction is increased. One would expect that an increase of energy dissipation will slow the mechanism.

F. INFLUENCE OF COEFFICIENT OF RESTITUTION

According to Figure 13, the fuze time increases considerably as the coefficient of restitution is varied from 0 to .5. Reference [1] shows that for $\epsilon = 0$, coupled motion follows immediately after impact. When $\epsilon = .5$, entrance action consists of four impacts, three of which are followed by free motion while the fourth is followed by coupled motion. Exit action shows two impacts with the last one followed by coupled motion. Each of the impacts is followed by escape wheel reversal. These multiple impacts and associated motion reversals seem to account for the observed increase in fuze time.

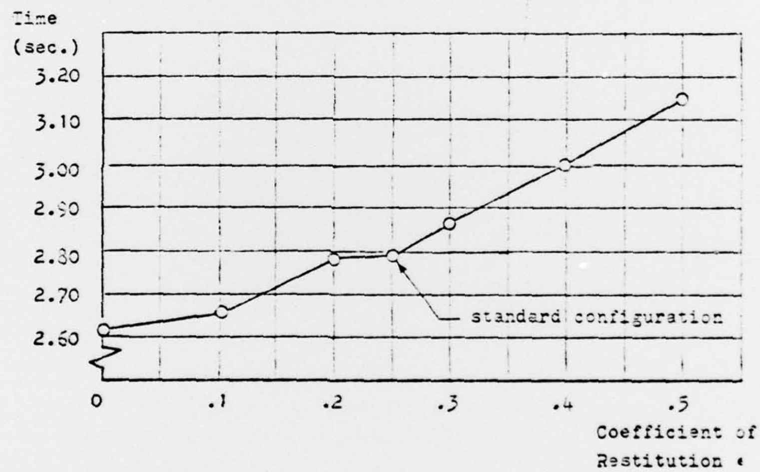

Figure 13 Influence of Coefficient of Restitution on Fuze Delay Time

7. REFERENCES

1. G. G. Lowen, and F. R. Tepper, "Dynamics of the Pin Pallet Runaway Escapement", in preparation as an ARRADCOM Technical Report.

2. M. E. Anderson and S. L. Redmond, "Runaway (Verge) Escapement Analysis and Guide for Designing Fuze Escapements," NWCCL TP 860, December 1969, Naval Weapons Center Corona Laboratory, Corona, CA 91720.

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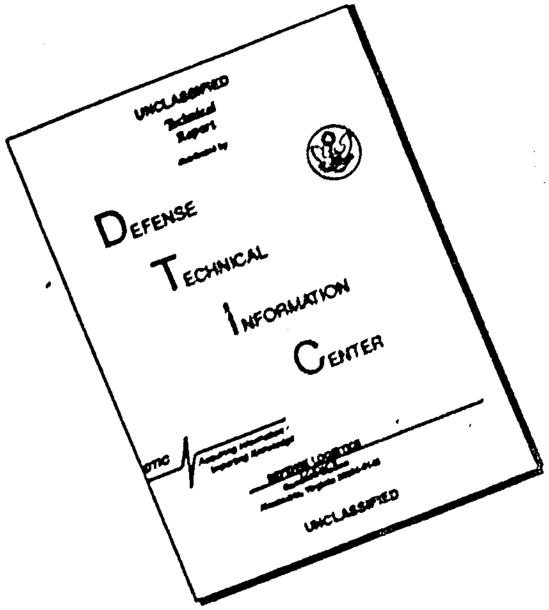

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